FOREWORD

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The work reported herein describes the results of the second study year, which was concerned with the evaluation of two candidate Shuttle Solid Rocket Booster case materials. The work conducted during the first study year was concerned with the evaluation of candidate materials for a metallic Shuttle Thermal Protection System and is reported in McDonnell Douglas Report No. MDC E0609. Both programs were conducted under the direction of Mr. J. G. Williamson of the Metallic Materials Branch, Materials Division of the George C. Marshall Space Flight Center, National Aeronautics and Space Administration. Mr. L. J. Pionke was the Program Study Manager for MDAC-E; Mr. K. C. Garland conducted the laboratory testing and assisted in data analysis and preparation of the final report. The authors wish to gratefully acknowledge the assistance of J. W. Davis and J. J. Slavic, who contributed in many ways throughout the program.

LUBRICATION OF SPACE SYSTEMS

Robert L. Fusaro
National Aeronautics and Space Administration
Lewis Research Center,
Cleveland, OH 44135

ABSTRACT

NASA has many high-technology programs planned for the future, such as the space station, Mission to Planet Earth (a series of Earth-observing satellites), space telescopes, and planetary orbiters. These missions will involve advanced mechanical moving components, space mechanisms that will need wear protection and lubrication. The tribology practices used in space today are primarily based on a technology more than 20 years old The question is, Is this technology base good enough to meet the needs of these future long-duration NASA missions? This paper examines NASA's future space missions, how mechanisms are currently lubricated, some of the mechanism and tribology challenges that may be encountered in future missions, and potential solutions to these future challenges.

INTRODUCTION

The space age brought with it many lubrication challenges that had not been experienced in the past: exposure to extremely low ambient pressures, a radiation and atomic oxygen environment, the presence of meteoroids, the absence of a gravitational field, imposed weight limitations, contamination by vapors, and the use of mechanical components that were not maintainable.

The challenges for future spacecraft appear to be even greater because missions are being planned that will require mechanisms to last for much longer periods of time. For example, the original design life of the space station was 30 years. Ideally, it will be built to last for 30 years. However, a 30-year maintenance-free life will be hard to accomplish because most mechanisms do not last that long on Earth without maintenance. The only mechanism with a long maintenance-free life that comes to mind is a refrigerator compressor.

In addition to Earth-orbiting spacecraft, luner and planetary missions are being planned that will require systems capable of operating over a temperature range of −181 to 111 °C, in a vacuum of 10^{-12} torr, and under extremely dusty conditions on the Moon and capable of operating under wide temperature ranges, in a low-oxygen atmosphere, and in a dusty, corrosive environment on the planet Mars.

This paper reviews the state of the art of lubrication as it applies to space. Lubrication techniques used in the past are described, and their advantages and disadvantages are discussed. In addition, lubrication challenges of future NASA space missions are examined.

FUTURE NASA SPACE MISSIONS

NASA has four major mission areas:

(1) Space Exploration Initiative (SEI)—Expand human presence to the Moon, Mars, and beyond.

(2) Mission to Planet Earth—Understand the interaction between oceans, atmosphere, and land (weather); living organisms and the environment; the environment and pollution; and the composition and evolution of the Earth.

(3) Astrophysics—Understand the universe (laws of physics, birth of stars and planets, and advent of life)

(4) Material and life sciences—Understand and develop new processes (fluid dynamics, combustion fundamentals, material processing, physics and chemistry, and space medicines)

Figure 1 shows a proposed timeframe for completing some of the hardware that will be needed for these missions. The figure separates the hardware classes into transportation, spacecraft, and large space systems.

NEED FOR IMPROVED LUBRICATION TECHNOLOGY

To determine if the state of the art of space mechanisms is adequate to meet the requirements of future NASA missions, a questionnaire was sent to industry and government personnel known to be working in the field. Unedited responses to the questionnaire are reported in (1). An analysis of the responses is reported in (2). The respondents answered a number of questions assessing current or anticipated needs. Approximately 98 percent stated that new or improved mechanical component and lubrication technology will be needed for future space missions. The complexity of the tribology problem is indicated in Figure 2, where the spectrum of operating speeds for future space mechanisms is shown.

METHODS USED TO LUBRICATE SPACE SYSTEMS

Liquids

Many different liquid lubricants have been used in space: silicones, mineral oils, perfluoropolyalkylethers (PFPAE), polyalphaolefins, polyolesters, and multiply-alkylated cyclopentanes. Table 1 lists some commonly used liquid space lubricants and their properties. For more details on these lubricants see (3–9).

Because excessive weight is a problem for satellites, large reservoirs of liquid lubricant and the resultant pumping systems (as used in aeronautical applications) are not appropriate. Instead, rolling-element bearings are lubricated with small liquid reservoirs and/or porous cages. The cages are impregnated with lubricant before assembly.

Lubricant can be lost through vaporization, creep, or inadequate supply. To counteract vaporization, low-vapor-pressure fluids, such as the PFPAE's, are used and labyrinth seals are employed. To counteract creep, barrier films are used, for example, in the lands of the races, to prevent the lubricant from creeping into undesirable places. To ensure adequate lubricant supply, positive feed systems have been developed to meter and control the flow of lubricant to the contact areas (10). Wick lubrication has also been proposed as a means of increasing the lubricant supply (11).

Greases

A grease is a semisolid liquid that consists of a liquid lubricant mixed with a thickener. The oil does the lubricating while the thickener holds the oil in place and provides a resistance to flow. Thickeners used consist of soaps (a metallic element such as lithium, calcium, sodium, or aluminum reacted with a fat or a fatty acid) or fine particles of a lubricating additive such as polytetrafluoroethylene (PTFE) or lead. The consistency of grease varies: it may be so hard that it must be cut with a knife or soft enough to flow under low pressures. As in oils, additives are often added to greases to improve load-carrying ability, oxidation resistance, and corrosion control.

Greases are used for a variety of space applications: low- to high-speed, angular-contact ball bearings; journal bearings; and gears. The primary reason for using a grease is that the grease can act as a reservoir for supplying oil to contacting surfaces. It can also act as a physical barrier to prevent oil loss by creep or by centrifugal forces. Greases used for various space applications are described by McMurtrey (3–4).

Solids

Solid lubricants are used in space to lubricate various mechanical components, such as rolling-element bearings, journal bearings, gears, bushings, electrical sliding contacts, clamps and latches, bolts, seals, rotating nuts, robotic and telescoping joints, backup bearings for gas and magnetic bearings, fluid transfer joints, various release mechanisms, valves, and harmonic drives. The following types of solid lubricants are used for these space applications:

(1) Soft metal films: gold, silver, lead, indium, and barium

(2) Lamellar solids: molybdenum disulfide, tungsten disulfide, cadmium iodide, lead iodide, molybdenum diselenide, intercalated graphite, fluorinated graphite, and pthalocyanines

(3) Polymers: PTFE, polyimides, fluorinated ethylene-propylene, ultra-high-molecular weight polyethylene, polyether ether ketone, polyacetal, and phenolic and epoxy resins

(4) Other low-shear-strength materials: fluorides of calcium, lithium, barium, and rare earths; sulfides of bismuth and cadmium; and oxides of lead, cadmium, cobalt, and zinc

The most common way to utilize a solid lubricant is to apply it to a metal surface as a film or coating. Typically, films are used only where it is not convenient or not possible to use a liquid or a grease. Since films have finite lives, they are typically not used for rolling-element bearing applications that would experience more than a million cycles of sliding.

There are many methods of depositing solid lubricant films onto a surface. The easiest method is to rub or burnish powders onto a roughened metallic surface. The next simplest method is to incorporate solid lubricant powders into a liquid binder system; brush, dip, or spray the mixture (much like a paint) onto the surface; and then thermally remove the liquid. More modern techniques include vacuum deposition methods, such as sputtering and ion plating. For more details on application techniques see (12).

Solid lubricants can also be employed as a solid body, typically in the form of a composite. A composite consists of a matrix material (to provide structural strength) and a solid lubricant material (to provide lubrication). Some polymer materials, such as the polyimides, have demonstrated that they can provide very low friction and wear properties by themselves without being made into a composite (13).

Rolling-element bearings are sometimes lubricated by making the retainer out of a composite lubricant material so that the lubricant can be transferred to the rolling balls and then to the inner and outer races. Figure 3 demonstrates how this film-transfer mechanism operates (14). Generally, this form of lubrication is successful only under lightly loaded conditions; however, the technique has been used with limited success to lubricate the ball bearings in the space shuttle turbopumps.

COMPARISON OF LIQUID AND SOLID LUBRICATION MECHANISMS

Liquid Lubrication Mechanisms

There are four defined regimes of liquid lubrication: hydrodynamic, elastohydrodynamic, boundary, and mixed. These regimes are directly proportional to the oil viscosity Z and to the relative velocity V and inversely proportional to the load L. Figure 4, known as the Stribeck-Hersey curve (15–17), depicts these regimes in terms of coefficient of friction versus the parameter viscosity, velocity, and load (ZV/L).

The first regime is known as hydrodynamic lubrication. This regime is characterized by the complete separation of the surfaces by a fluid film that is developed by the flow of a fluid through the contact region. Typically, the thickness of the lubricant film separating the surfaces is greater than 0.25 μm (10^{-5} in.).

For nonconformal concentrated contacts, where loads are high enough to cause elastic deformation of the surfaces but speed and viscosity are not large enough to produce film thicknesses greater than 0.25 μm (10^{-5} in.), the second lubrication regime comes into effect. This regime is known as elastohydrodynamic lubrication. The thickness of the lubricant film in this regime is 2.5 μm (10^{-4} in.) to 0.025 μm (10^{-6} in.). Usually, during hydrodynamic and elastohyrodynamic lubrication, no wear takes place because there is no contact between the sliding surfaces.

As the thickness of the oil film decreases to values below 0.0025 μm (10^{-7} in.), the boundary lubrication regime comes into play. In this regime asperity contact between the sliding surfaces takes place, and the lubrication process becomes the shear of chemical compounds on the surface. This regime is dependent on lubricant additives within the oil that produce compounds on the surface which have the ability to shear and provide lubrication. Boundary lubrication is highly complex, involving surface topography, physical and chemical adsorption, corrosion, catalysis, and reaction kinetics. The transition between elastohydrodynamic and boundary lubrication is not sharp, and there exists a region, called the mixed lubrication regime, which consists of some elastohydrodynamic and some boundary lubrication.

Other Factors Affecting Liquid Lubrication

Many factors influence liquid lubrication besides viscosity, speed, and load. Probably the most influential parameter is temperature. Temperature affects the viscosity of oil, which vaporizes at some high temperature or becomes too thick to flow freely at some low temperature. Because oils tend to oxidize, oxidation inhibitors must be added. Sometimes oils contain certain chemicals that corrode metallic surfaces. In some cases the bearing surfaces themselves can initiate the chemical breakdown or polymerization of oils (especially fluorocarbon oils (18–20)). Oils can attack seals and cause them to shrink or swell, and sometimes oils have a tendency to foam, which can cause lubricant starvation.

Thus, in addition to adding chemicals to oils to make them better boundary lubricants, many other types of chemicals must be added to make oils effective lubricants. For more information on the theory of lubrication and the types of additives needed in oils see Booser (21).

Solid Lubrication Mechanisms

Solid lubrication is essentially the same as boundary lubrication (with liquids), except that there is no liquid carrier to resupply a solid material (such as a chemical reactant) to the surfaces to produce a lubricating solid film. Instead, a solid film must be applied to the sliding surfaces before sliding commences, and this film must last for the life of the component. An alternative to using a film is to make a part of the bearing (e.g., the bearing cage) out of a solid lubricant material or a solid lubricant composite material.

When using films or coatings two basic lubrication mechanisms must be considered (22). The first mechanism is illustrated in Figure 5 (22), where a metallic pin is sliding against a film applied to a sandblasted disk. This mechanism is applicable to thin film lubrication where loads are very high. The mechanism involves the shear of an extremely thin layer of solid lubricant (usually less than 2 μm thick) between a transfer film on the counterface surface (pin or rider in pin-on-disk testing) and the film itself on the substrate surface. The lubrication process is dynamic. Lubricant builds up in the entrance area of the pin and flows across the pin contact area and out the exit area of the pin. Flow also takes place on the substrate surface (disk in pin-on-disk testing). Having a rough substrate surface is helpful for two reasons: (1) It helps prevent lateral flow of solid lubricant from the contact area, and (2) the valleys between the asperities serve as reservoirs for solid lubricant materials. The disadvantage of rough surfaces is that sharp asperity peaks can increase run-in wear; however, the surface topography can be controlled to minimize this.

The effect on endurance life of applying molybdenum disulfide (MoS_2) films to surfaces with different roughnesses is shown in (23). Endurance lives in that study were obtained for MoS_2 films applied to polished, sanded, and sandblasted surfaces. The sanded surface provided up to 20 times, and the sandblasted surface provided up to 400 times, the endurance life of the polished surface.

The second mechanism takes place when a coating (thick film) is employed. For this mechanism to work the coating must be capable of supporting the load. The lubrication process will then involve the shear between a transfer film on the pin and the thin, ordered solid lubricant layer on the coating surface. The wear process is one of gradual wear through the coating. Figure 6 shows actual cross-sectional areas of a polyimide-bonded graphite fluoride film after experiencing a pin sliding over it for various sliding intervals. Note that the vertical magnification is 50 times the horizontal magnification to emphasize the wear process. Initially, the film asperities were capable of supporting the load, and it could be seen by high- magnification optical microscopy that an extremely thin shear layer had developed on the coating surface It took 3500 kilocycles of sliding to wear through this 40-μm-thick coating and reach the metallic surface.

The advantage of this lubrication mechanism is that once the metallic surface is reached by the pin (counterface), continued lubrication can occur by the first mechanism (i.e., shear of a thin film on the metallic surface). Thus, much longer endurance lives are obtainable with coatings. This particular coating had an endurance life of 8500 kilocycles. Studies have shown that the rate of this particular coating wear was determined by the load and by the contact area of the metallic slider (24). Reducing the contact area or the load extended the endurance life.

One caveat to be aware of in this wear process is that if the coating does not have the strength to support a particular load, it will quickly be worn away (either it will plastically deform or brittlely fracture, debonding from the surface). This result is not necessarily bad because a "secondary film" can form from wear debris and/or material that has not been debonded. However, if the film is too thick or the geometry is not correct, the secondary film may not form at all. Thus, it is important to know how thick to apply a film. A thin film has a better chance of forming a very thin shear film than does a coating (a thick film) that will not support the load. With a thin film there is less chance of wear particles escaping the contact area during film deformation (known as run-in).

Other Factors Affecting Solid Lubrication

Many factors or conditions also affect solid lubricant performance: type of substrate material onto which a solid lubricant film is deposited, surface finish of substrate material, type of counterface material, surface finish of counterface material, surface to which a solid lubricant film is applied, surface hardness of substrate and counterface materials, geometry of sliding specimens, contact stress or pressure, temperature, sliding speed, and environment (atmosphere, fluids, dirt). Depending on the particular solid lubricant employed, changing the value of just one of these parameters can alter the coefficient of friction, wear rate, or endurance life. Also, a point to remember is that low friction does not necessarily correlate to low wear or long endurance lives. For a more detailed discussion of how these factors affect solid lubricant performance see (12). One cannot specify a wear rate or a coefficient of friction without knowing all the conditions under which the mechanism will be operating.

Advantages and Disadvantages of Solid and Liquid Lubricants

Some of the various difficulties associated with using solid and liquid lubricants have been discussed in previous sections of this article. Table 2 summarizes the advantages and disadvantages of using liquid lubricants for space applications; and Table 3 summarizes the advantages and disadvantages for using solid lubricants for space applications.

FUTURE SPACE TRIBOLOGICAL CHALLENGES

Spacecraft

Kannel and Dufrane (25) conducted a study of the tribological problems that have occurred in the past and are projected to occur in future space missions. Figure 7 (25) is a qualitative chart which illustrates that despite significant advances in tribology, the demands on tribology for future space missions will grow faster than the solutions.

Lubrication problems in space are dependent on the particular application. In many cases there are no loads on bearings in space and they have to be preloaded. Also many bearings in Earth orbit operate predominantly in the elastohydrodynamic lubrication regime. For these reasons the stresses on the oils may not be as great in Earth orbit as they are on the ground. Thus, the lubricants employed have produced fairly good success over the years. However, loss of lubricant through vaporization, creep, and degradation has caused some bearings to fail before their missions were complete.

In an attempt to reduce vaporization (and also contamination) new synthetic lubricants, such as the PFPAE's, have been employed that have extremely low evaporation rates (8). These lubricants also have excellent viscosity characteristics. Although, in theory, these lubricants appear to be exceptional, in operation some failures have occurred from chemical breakdown. Researchers have shown that the presence of chemically active surfaces and/or wear particles combined with exposed radicals in the fluid will inevitably result in acidic breakdown of the lubricants (18–20). More research needs to be done to understand this breakdown process in order to make synthetic lubricants reliable. Another problem with these lubricants is that traditional mineral oil additives are not soluble in them. New additives need to be developed for these PFPAE lubricants.

Solid lubricant films are used where it is not convenient to use liquid lubricants or where contamination might be a problem. As mentioned previously, solid lubricant films have finite lives. As a general rule of thumb they are not employed where they will experience more than 1 million sliding cycles. An additional problem with some solids is that sometimes powdery wear particles can be produced which can pose a contamination problem on sensitive surfaces. There is a need to develop solid lubricant films that will provide longer endurance lives and not produce powdery wear particles.

A significant problem for space lubrication is the lack of oxygen. Oxide layers on metals play an important role in the boundary film lubrication process. On Earth most surfaces are covered with oxide films, these films help to prevent adhesion between surfaces. In a vacuum, if these oxides are removed (by the sliding process), they cannot be reformed as they are on Earth and severe wear of metallic surfaces will occur. This is one reason that boundary additives are necessary in oils; that is, if for some reason metal-to-metal contact occurs and removes an oxide film, the additives can then reform an oxide film or some other type of surface film to prevent future metal-to-metal contact. In the case of nonlubricated sliding or solid lubricant sliding, where oxide films cannot be replaced if worn away, catastrophic failure can occur. Thus, it is important for any metallic surface sliding in a vacuum to be covered with some type of film to prevent metal-to-metal contact.

Atomic oxygen is the major constituent in a low-Earth-orbit environment. NASA has just recently recognized it as being an important consideration in the design of long-lived spacecraft (27). Experiments on two space shuttle missions (STS 5 and 6) as well as with the Long Duration Exposure Facility (LDEF) have shown that material surfaces can change when exposed to atomic oxygen. Carbon, silver, and osmium have been found to react quickly enough to produce macroscopic changes in their structures. Carbon reacts to form volatile oxides. Silver forms heavy oxide layers that eventually flake or spall, resulting in material loss.

Polymers, such as epoxies, polyurethanes, and polyimides, also have been found to be reactive with atomic oxygen. The reaction efficiency did not seem to be strongly dependent on chemical structure however.

Some representative reaction efficiencies are shown in Table 4. The efficiencies are expressed as the volume of material lost per incident oxygen atom. The data indicate that using polymers (either as binders or alone as solid lubricants) may not be appropriate if the polymer is to undergo long exposure to atomic oxygen. Preliminary indications are that atomic oxygen also degrades MoS_2.

Planetary Surface Vehicles and Lunar Processing Plants

It is anticipated that when a manned outpost is established on the Moon, the high vacuum (10^{-12} torr) combined with the fine abrasive dust will have a deleterious effect on sliding components, especially if they are unlubricated. The dust will accelerate the removal of protective oxide films on metals. This could especially be a problem with "track type" vehicles. In addition to being abrasive, the dust is also positively charged; thus it will have a tendency to adhere to everything. Lubricants, both liquid and solid, will have to be sealed so that the dust cannot invade them. New concepts in sealing will be needed.

Another anticipated problem on the Moon is the wide temperature extremes. In the daytime the temperature can reach 111 °C; at night it can fall to −181 °C, as was found during the Apollo missions (28). And because the Moon's rotation rate is low, days and nights on the Moon are 14 Earth days long. (By contrast to the lunar temperature, recorded temperature extremes on the surface of the Earth range from −88.3 °C in Antarctica in 1960 and to 58.0 °C in Libya in 1922 (29).) Currently, no liquid lubricants will operate at these cold lunar temperatures. Either the lubricants will have to be heated (which will expend precious energy) or solids must be employed. Even so, this is an area where little technology research has been performed. Research needs to be conducted to better understand how to lubricate at these low temperatures.

In addition, the Moon has no protective atmosphere to shield mechanical equipment and their tribological systems from solar and cosmic radiation. There is no long-term experience as to how equipment will perform under these conditions.

Space Simulation Problems

Because the tribological properties of materials are extremely system dependent (i.e., the friction, wear, and lubricating ability are strongly dependent on such operating conditions as load, speed, type of contact, temperature, and atmosphere), it is imperative that technology testing simulate as closely as possible the particular space application. The vacuum, load, speeds, etc., can be simulated fairly easily on the ground, but it is not as easy to simulate zero gravity or the radiation/atomic oxygen environment of low Earth orbit.

Also difficult to simulate through technology testing are the forces and vibrations experienced by mechanical components during launch. These parameters can cause a lubricant or component to fail immediately, or they can decrease the life predicted through ground-based testing.

Problems can also occur through storage of satellites. Satellites are sometimes stored for years before launch. Oils tend to creep away from contact zones, s lubricants can oxidize or absorb water and decrease their lubricating ability, etc. More research needs to be done in these areas to determine which parameters are important and which are not important.

Accelerated Testing Problems

Designers would like to know how long a particular mechanical component will operate before it fails. Presently, the only way to ascertain this is to operate the mechanism in a full-scale ground test. The problem is that these tests may have to run for years. Accelerated testing can be done on some solid lubricants because wear rate is often speed independent. When this is the case, the sliding speed can be simply increased to increase the number of sliding cycles.

Because liquid lubrication is not speed independent, speed cannot be increased to accelerate the test. Therefore, a better understanding of the failure mechanisms of liquid lubricants is needed so that these mechanisms can be analytically modeled to simulate a life test. It may be possible to determine failure precursors on bearing surfaces (such as chemical changes or microcracks) by using surface science. Knowing these precursors would allow us to predict bearing life under various testing conditions and to make corrections that would extending bearing life.

POTENTIAL NEW LUBRICATION TECHNOLOGIES

Dense Thin Films of Solid Lubricants

Sputtered MoS_2 coatings have been used as lubricants for many years (30,31). Recent improvements in sputtering technology by programs conducted at the National Centre of Tribology in the United Kingdom (32) and by programs sponsored by the Strategic Defense Initiative (SDI) (33–35) have produced dense, thin films of sputtered MoS_2 that have exhibited extremely low friction coefficients (as low as 0.01) and long endurance lives (millions of revolutions in a space bearing). These films show considerable promise for space applications where billions of cycles are not required.

Powder Lubrication

Heshmat (36,37) has been investigating the use of fine powders to lubricate rolling-element and sliding bearings. His studies have indicated that the powders (under certain conditions) flow much like liquids in hydrodynamic lubrication. The results are preliminary, but they suggest the potential for using powders to lubricate at high temperatures where liquids will not function.

Novel Noncontact Lubrication Solutions

An alternative to using oils or solids to lubricate a moving component is to use a high-pressure gas film, either externally pressurized as in a hydrostatic gas bearing or self-acting as in a hydrodynamic foil bearing. Gas bearings have been used for many years. One problem with them is that at startup or shutdown the sliding surfaces come into contact, so that they have to be hydrostatically elevated or coated with a solid lubricant to lubricate the surfaces during these intervals (38). Also overloads and shock loads can cause high-speed sliding contact, further demonstrating the need for a solid lubricant coating. Gas bearings are somewhat limited in their load-carrying ability, but they work well for high-speed applications.

Magnetic Bearings

Magnetic bearings essentially use opposing magnetic fields to separate the sliding surfaces. Usually, a combination of permanent and electromagnetic materials is used. Magnetic bearings are not widely used today, but they have considerable promise for future lubricating systems (39). One of the problems inhibiting their use has been that complicated and heavy electronic systems are required to ensure their success. With the development of improved electronics in recent years the future use of magnetic bearings appears promising. Solid lubricant coatings must be incorporated into the design of these bearings to prevent wear damage during an occasional bump.

Hard Coatings

In general, hard coatings are not considered to be lubricants, but they do prevent wear and sometimes reduce friction. To date, not many "nonlubricating" coatings have been used in space applications. Miyoshi (40–42) has shown that these materials have considerable promise for use in space systems. I believe that hard coatings could be used in conjunction with layer lattice solid lubricants to help extend endurance lives. In addition, they might be used with liquid lubricants to reduce friction and wear during boundary lubrication. There are many other potential applications.

In Situ Sputtering of Solid Lubricants

Although it has not been attempted yet, I suggest that, because many space applications occur in a vacuum, it may be possible to develop sputtering systems that could sputter a solid lubricant material onto a surface while it is in operation. This would be one way of resupplying solid lubricant films and essentially providing infinite endurance life.

CONCLUDING REMARKS

This article has presented an overview of the current state of the art of tribology, some current and future perceived space lubrication problem areas, and some potential new lubricating technologies. It is my opinion that tribology technology, in general, has not significantly advanced over the last 20 to 30 years, even though some incremental improvements in the technology have occurred. We have a better understanding of elastohydrodynamic lubrication, some new lubricating and wear theories have been developed, and some new liquid and solid lubricants have been formulated. However, the important problems of being able to lubricate reliably at high temperatures or at cryogenic temperatures have not been adequately addressed.

The need is even greater in the area of space tribology: little new lubrication technology has been developed for use in space since the Apollo years. The same technology is still being used today, 20 years later. The technology has worked adequately for most NASA missions that have flown to date; but as NASA plans longer duration, more demanding missions, the technology will not be sufficient.

REFERENCES

1. Fusaro, R.L., "Government/Industry Response to Questionnaire on Space Mechanisms/Tribology Technology Needs," NASA TM–104358 (1991).
2. Fusaro, R.L., "Space Mechanisms Needs for Future NASA Long Duration Space Missions," AIAA/NASA/OAI Conference on Advanced SEI Technologies, AIAA Preprint 91–3428 (1991).
3. McMurtrey, E.L., "Lubrication Handbook for the Space Industry," NASA TM–86556 (1985).
4. McMurtrey, E.L., High Performance Solid and Liquid Lubricants—An Industrial Guide, Noyes Data Corporation, Park Ridge, NJ (1987).
5. Zaretsky, E., "Liquid Lubrication in Space," Tribology International, 23, 75 (1990).
6. Babecki, A.J., Grenier, W.G., and Haehner, C.L., "An Evaluation of Liquid and Grease Lubricants for Spacecraft Applications," NASA TM–82275 (1976).
7. Delaat, F.G.A, Shelton, R.V., and Kimzey, J.H., "Status of Lubricants for Manned Spacecraft," Lubr. Eng., 23, 145 (1967).
8. Conley, P.L., and Bohner, J.J., "Experience with Synthetic Fluorinated Fluid Lubricants, Proceedings of the 24th Aerospace Mechanisms Symposium, April 18-20, 213 (1990).
9. Venier, C.G., and Casserly, E.W., Multipy-Alkylated Cyclopentanes (MACs): A New Class of Synthesized Hydrocarbon Films, Lubr. Eng., 23, 586 (1990).
10. James, G.E., "Positive Commandable Oiler for Satellite Bearing Lubrication," NASA CP–2038, 87–95, (1977).

11. Lowenthal, S.H., Scibbe, H.W., Parker, R.J., and Zaretsky, E.V., "Operating Characteristics of a 0.87 kW-hr Flywheel Energy Storage Module," Proceedings of the 20th Intersociety Energy Conversion Engineering Conference (IECEC), Vol. 2, 164 (1985).

12. Fusaro, R.L., "How to Evaluate Solid-Lubricant Films Using a Pin-on-Disk Tribometer," Lubr. Eng., 43, 330 (1986).

13. Fusaro, R.L., "Polyimides—Tribological Properties and Their Use as Lubricants, Polyimides: Synthesis Characterization, and Applications, Vol. 2, K.L. Mittal, ed., Plenum Press, New York, 1053–1080 (1984).

14. Brewe, D.E., Scibbe, H.W., and Anderson, W.J., "Film-Transfer Studies of Seven Ball-Bearing Retainer Materials in 60 °R (33 K) Hydrogen Gas at 0.8 Million DN Value," NASA TN D–3730 (1966).

15 Stribeck, R., "Characteristics of Plain and Roller Bearings," Ziet. V.D.I., 46 1341 (1902).

16. Hersey, M.D., "The Laws of Lubrication of Horizontal Journal Bearings," J. Wash. Acad. Sci., 4, 542 (1914).

17. Jones, W.R., Jr., "Boundary Lubrication Revisited," NASA TM–82858 (1982).

18. Carrè, D.J., "The Performance of Perfluoropolyalkylether Oils Under Boundary Lubrication Conditions," ASLE Trans., 31, 437, (1987).

19. Carrè, D.J., "Perfluoropolyalkylether Oil Degradation: Influence of FeF_3 Formation on Steel Surfaces Under Boundary Conditions," ASLE Trans., 29, 121 (1986).

20. Zehe, M.J., and Faut, O.D., "Acidic Attack of Perfluorinated Alkyl Ether Lubricant Molecules by Metal Oxide Surfaces," STLE Trans., 33, 4, 634–640 (1990).

21. Booser, R.E., ed., CRC Handbook of Lubrication, Vol. 2, Theory and Design, CRC Press, Boca Raton, FL (1984).

22. Fusaro, R.L., "Mechanisms of Lubrication and Wear of a Bonded Solid-Lubricant Film, ASLE Trans., 24, 191 (1981).

23. Fusaro, R.L., "Lubrication and Failure Mechanisms of Molybdenum Disulfide Films, II—Effect of Substrate Roughness," NASA TP–1379 (1978).

24. Fusaro, R.L., "Effect of Load, Area of Contact and Contact Stress on the Wear Mechanisms of a Bonded Solid Lubricant Film," Wear, 75, 403 (1982).

25. Kannel, J.W., and Dufrane, K.F., "Rolling Element Bearings in Space," The 20th Aerospace Mechanisms Symposium, NASA CP-2423, 121–132 (1986).

26. Kannel, J.W., Dufrane, K.F., Barber, S.A., and Gleeson, J., "Development of Improved Self-Lubricating Cages for SSME HPOTP Bearings," Advanced Earth-to-Orbit Propulsion Technology 1988, NASA CP-3012, 175–189 (1988).

27. Leger, L.J., and Dufrane, K.F., "Space Station Lubrication Considerations," The 21st Aerospace Mechanisms Symposium, NASA CP-2470, 285–294 (1987).

28. Taylor, S.R., Planetary Science: A Lunar Perspective, Houston: Lunar and Planetary Institute (1982).

29. McWhirter, N., ed., Guiness Book of World Records, Enfield, England (1979).

30. Spalvins, T., and Przybyszewski, J.S., "Deposition of Sputtered Molybdenum Disulfide Films and Friction Characteristics of Such Films in Vacuum," NASA TN D-4269 (1967).

31. Spalvins, T., "Bearing Endurance Tests in Vacuum for Sputtered Molybdenum Disulfide Films," NASA TM X-3193 (1975).

32. Roberts, E.W., "Ultralow Friction Films of MoS_2 for Space Applications," Thin Solid Lubr. Films, 181, 461 (1989).

33. Fleischauer, P.D., and Bauer, R., "Chemical and Structural Effects on Lubrication Properties of Sputtered MoS_2 Films," Tribology Trans., 31, 239 (1988).

34. Fleischauer, P.D., Lince, J.R., Bertrand, P.A, and Bauer, R, "Electronic Structure and Lubrication Properties of MoS_2—A Qualitative Molecular Orbital Approach, Langmuir, 5, 1009 (1989).

35. Hilton, M.R., Bauer, R., Didziulis, S.V., Lince, J.R., and Fleischauer, P.D., "Structural, Chemical and Tribological Studies of Sputter-Deposited MoS_2 Solid Lubricant Films," Advances in Engr. Trib., Y.W. Chung and H.S. Cheng, eds., STLE SP-31, 37–42 (1991).

36. Heshmat, H., "The Rheology and Hydrodynamics of Dry Powder Lubrication," STLE Trans., 34, 433 (1991).

37. Heshmat, H., "Wear Reduction Systems: Powder Lubricated Piston Rings for Coal-Fired Diesel Engines," Proceedings of the Advanced Research and Tech. Dev. Direct Utilization, Instrumentation and Diagnostic Contractors Review Meeting, D.W. Greiling and P.M. Goldberg, eds., DOE/Metc-90 6108–VOL–1, 281–300 (1989).

38. Bhushan, B., "Development of Surface Coatings for Air Lubricated Bearings to 650 °C," ASLE Trans., 23, 185 (1980).

39. Fleming, D., "Magnetic Bearings—State of the Art," NASA TM–104465 (1991).

40. Miyoshi, K., "Tribological Studies of Amorphous Hydrogenated Carbon Films in a Vacuum, Spacelike Environment," Applications of Diamond Films and Related Materials, Y. Tzeng, M. Yoshikawa, M. Murakawa, and A. Feldman, eds., Elsevier Science Publishers B.V. (1991).

41. Miyoshi, K., "Friction and Wear of Plasma-Deposited Amorphous Hydrogenated Films on Silicon Nitride," Adv. Info. Storage Syst., 3, 147 (1991).

42. Miyoshi, K., "Fundamental Tribological Properties of Ion-Beam-Deposited Boron Nitride Thin Films," Materials Science Forum, 54, 375 (1990).

TABLE 1.—PROPERTIES OF SOME COMMONLY USED SPACE LUBRICANTS

Type of lubricant	Average molecular weight	Viscosity at 20 C, cSt	Viscosity index	Pour point, °C	Vapor pressure, Pa	
					At 20 °C	At 100 °C
KG–80, mineral oil	--------	520	101	-9	1×10^{-6}	------
Apiezon C, mineral oil	574	250	----	–15	5×10^{-7}	------
BP 110, mineral oil	--------	120	108	–24	5×10^{-7}	------
BP 135, ester	--------	55	128	–45	1×10^{-6}	------
Nye 179, polyalphaolefin	--------	[a]30	139	<–60	9×10^{-7}	------
Nye UC7, neopentylpolyolester	--------	75	----	–56	7×10^{-7}	------
Nye UC4, neopentylpolyolester	--------	44	----	------	3×10^{-6}	------
$SiHC_1$, silahydrocarbon, type 1	1 480	278	125	–50	-------	------
$SiHC_2$, silahydrocarbon, type 2	1 704	480	128	–15	-------	------
Fomblin, PFPAE (Bray 815Z)	9 500	255	355	–66	4×10^{-10}	1×10^{-6}
Krytox, PFPAE	11 000	2717	----	–15	4×10^{-12}	1×10^{-7}
Demnum, PFPAE	8 400	500±25	210	–53	7×10^{-9}	1×10^{-5}

[a]Viscosity at 40 °C.

TABLE 2.—ADVANTAGES AND DISADVANTAGES OF USING LIQUID LUBRICANTS

Advantages	Disadvantages
Long endurance lives if properly employed	Finite vapor pressure (oil loss and contamination)
Low mechanical noise in most lubrication regimes	Lubrication temperature dependent (viscosity, creep, vapor pressure)
Promotion of thermal conductance between surfaces	Seals or barrier coatings needed to prevent creep
Very low friction in elastohydrodynamic lubrication regime	Friction (viscous) dependent on speed
No wear in hydrodynamic or elastohydrodynamic regimes	Endurance life dependent on lubricant degradation or loss
No wear debris	Electrically insulating
	Additives necessary for boundary lubrication regime
	Long-term storage difficult
	Accelerated testing difficult if not impossible

TABLE 3.—ADVANTAGES AND DISADVANTAGES OF USING SOLID LUBRICANTS

Advantages	Disadvantages
Negative vapor pressure (no contamination)	Endurance life dependent on operating conditions, e.g., - Atmosphere (air, vacuum, etc.) - Sliding speed - Load and contact geometry
Wide operating temperature range	Finite life
No migration of lubricants	Some wear - Opening up clearances - Producing wear debris
Good boundary lubrication and electrical conductivity	Poor thermal characteristics (no heat dissipation)
Minimal degradation	Reapplication difficult or impossible
Accelerated testing possible	Heavy transfer (can produce erratic torque at low speeds)
Good long-term storage	Inability to be evaluated in air for use in vacuum
No viscosity effects	
Corrosion protection	

TABLE 4.—REACTION EFFICIENCIES OF SELECTED TRIBOMATERIALS WITH ATOMIC OXYGEN IN LOW EARTH ORBIT

[From (27).]

Material	Reaction efficiency, cm^3/atom
Kapton	3.0×10^{24}
Mylar	3.4
Tedlar	3.2
Polyethylene	3.7
Polysulfone	2.4
1034C graphite/epoxy	2.1
5208/T300 graphite/epoxy	2.6
Epoxy	1.7
Silicones	1.7
PTFE	<.05
Carbon (various forms)	0.9×10^{24} to 1.7×10^{24}
Silver	Heavily attacked

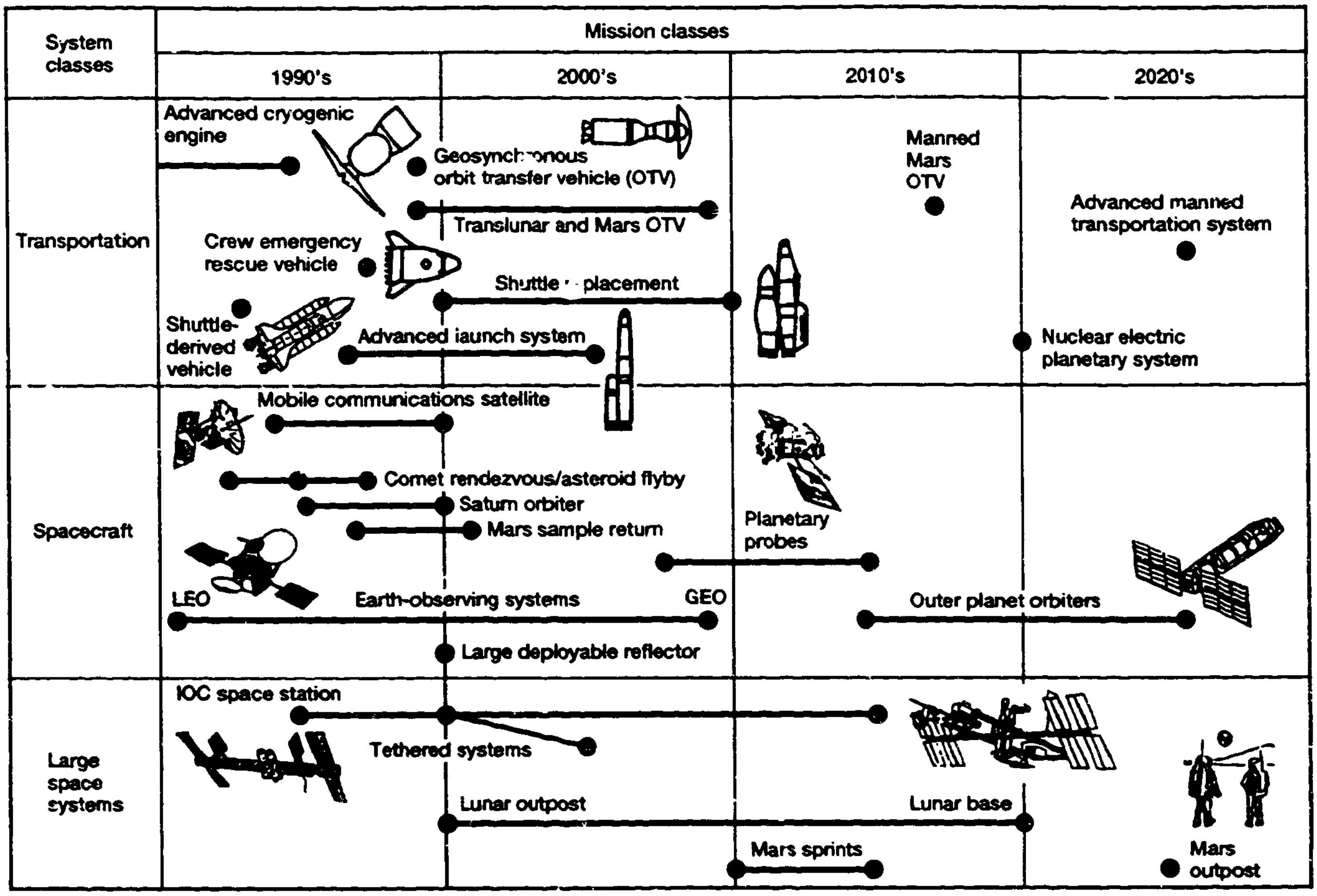

Figure 1.—Proposed timeframe for future NASA missions.

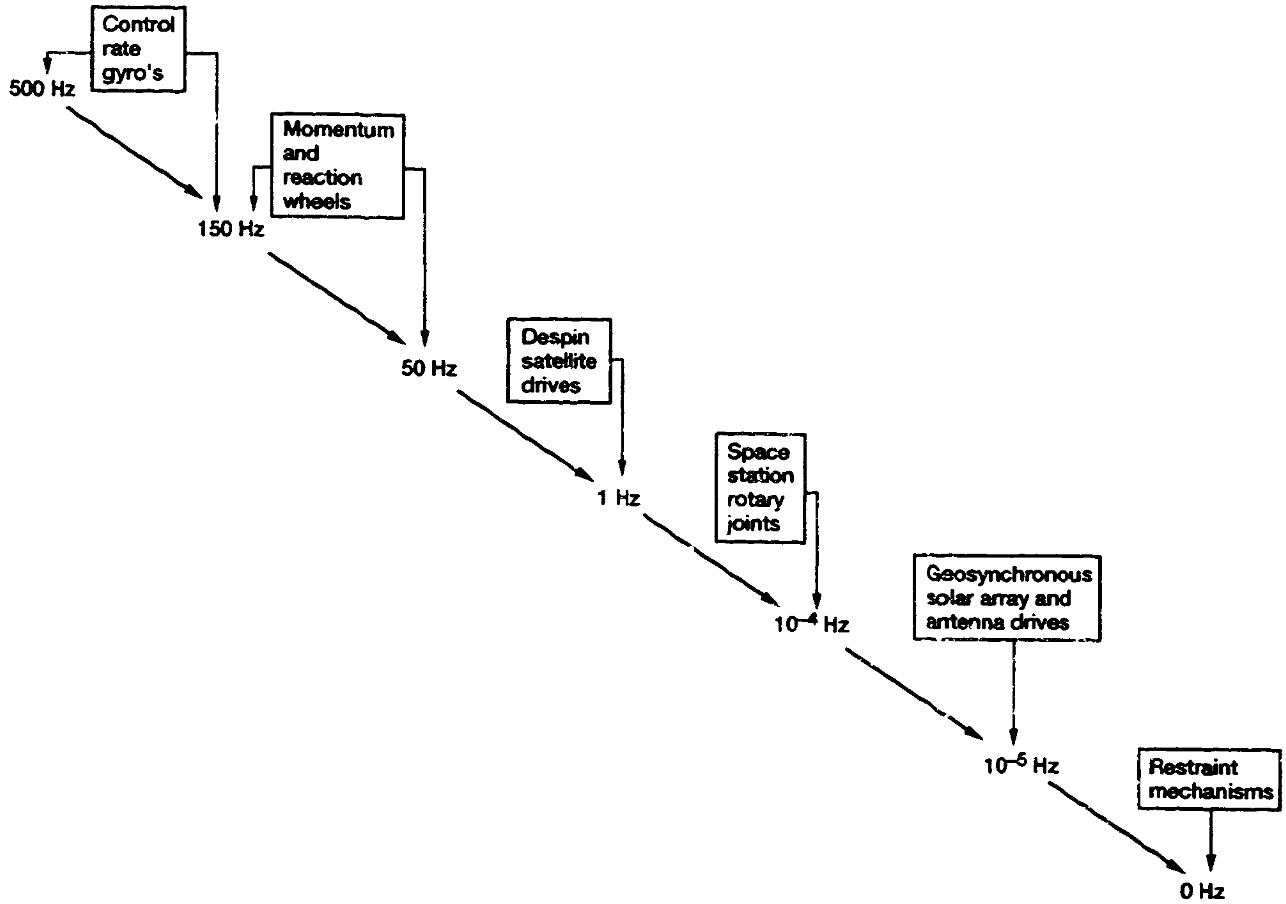

Figure 2.—Spectrum of speeds seen by space mechanisms.

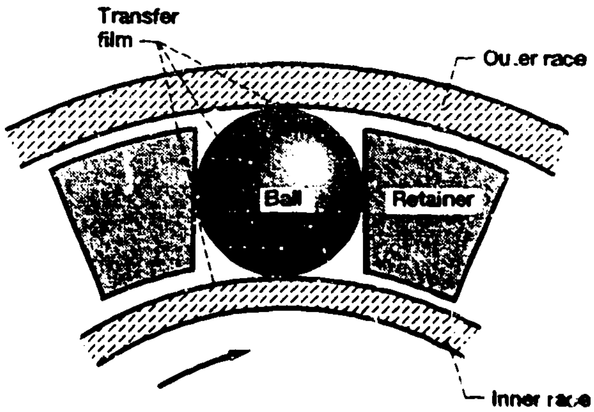

Figure 3.—Illustration of ball bearing film-transfer mechanism (14).

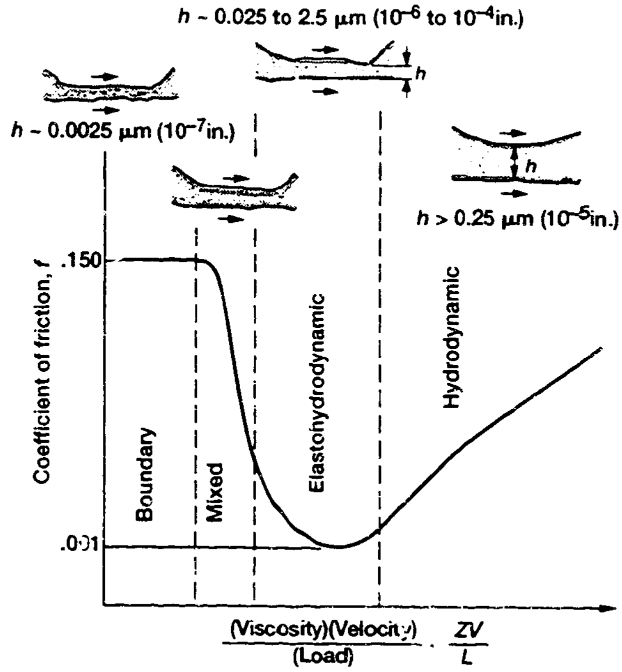

Figure 4.—Coefficient of friction as function of viscosity-velocity-load parameter (Stribeck-Hersey curve (17)); h = film thickness.

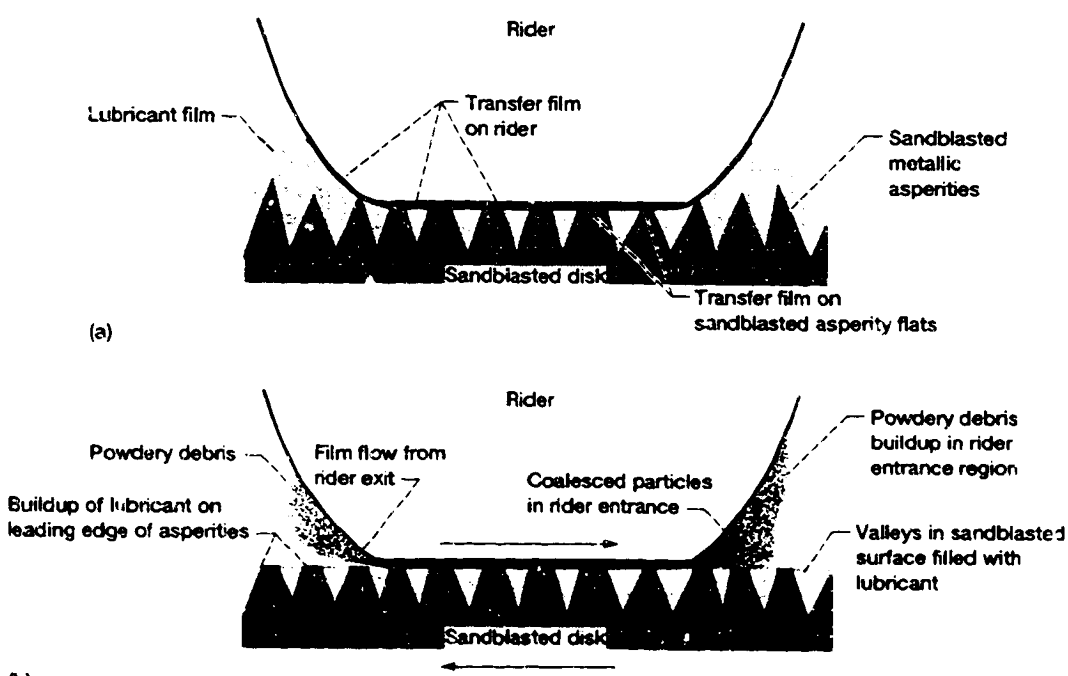

Figure 5.—Idealized schematic drawing of sliding surfaces, illustrating first lubrication mechanism. (a) Front view, rider sliding out of page. (b) Side view, rider sliding left to right.

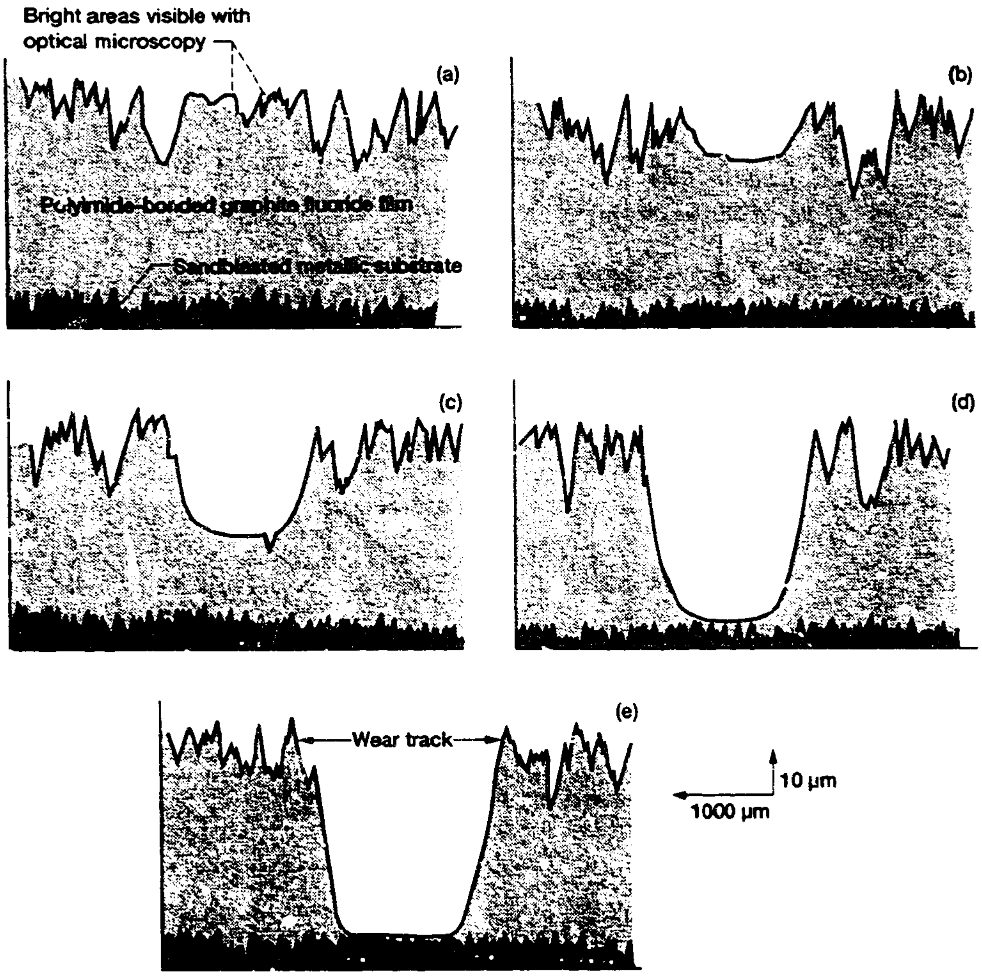

Figure 6.—Surface profiles taken after various sliding intervals for 0.95-mm-diameter pin flat sliding on polyimide-bonded graphite fluoride film (22). (a) Sliding interval, 15 kilocycles. (b) Sliding interval, 500 kilocycles. (c) Sliding interval, 1500 kilocycles. (d) Sliding interval, 3500 kilocycles. (e) Sliding interval, 8500 kilocycles.

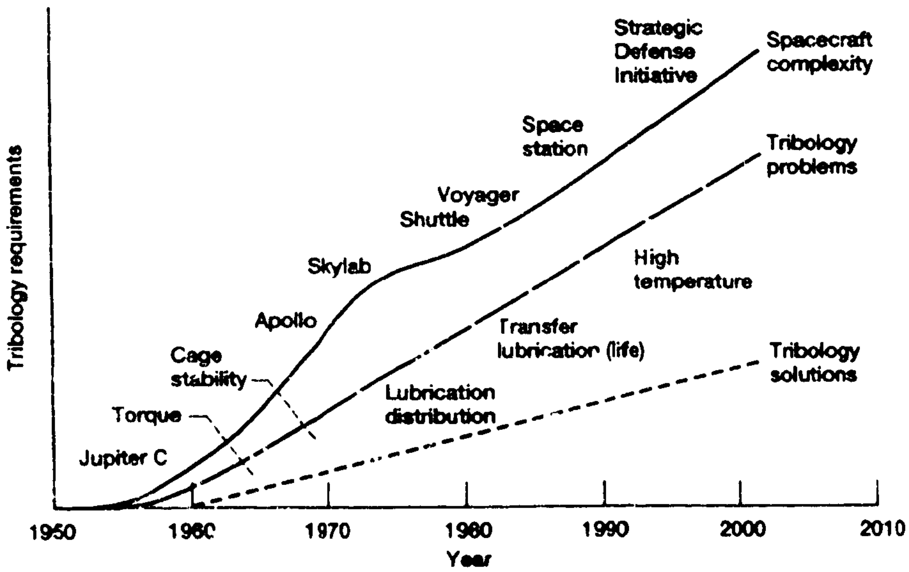

Figure 7.—Growth of tribology requirements with advances in space (25).

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13. ABSTRACT ***(Maximum 200 words)***

NASA has many high-technology programs planned for the future, such as the space station, Mission to Planet Earth (a series of Earth-observing satellites), space telescopes, and planetary orbiters. These missions will involve advanced mechanical moving components, space mechanisms that will need wear protection and lubrication. The tribology practices used in space today are primarily based on a technology that is more than 20 years old. The question is, Is this technology base good enough to meet the needs of these future long-duration NASA missions? This paper examines NASA's future space missions, how mechanisms are currently lubricated, some of the mechanism and tribology challenges that may be encountered in future missions, and some potential solutions to these future challenges.

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